

Characterizing the Subsurface Geology In and Around the U.S. Army Camp Stanley Storage Activity, South-Central Texas

The authors show how the U.S. Geological Survey acquired new downhole geophysical and petrophysical data and constructed a 3D EarthVision™ model to better understand the geological controls on groundwater flow and (or) direction in and around the U.S. Army Camp Stanley Storage Activity (CSSA).

The geologic framework and hydrologic characteristics of aquifers are important components for understanding the Nation’s subsurface geology and predicting its hydraulic budgets. Integrating surface lithostratigraphic and hydrostratigraphic mapping can help characterize the spatial distribution and hydraulic connectivity of an aquifer’s permeable zones. Three-dimensional (3D) geologic modeling of an aquifer system can quantitatively characterize the connectedness of rock units across fault and fracture zones and enable geoscientists to visualize the spatial relations between the saturated and unsaturated stratigraphic units. Three-dimensional geologic framework model data can also be integrated into groundwater flow models, such as those constructed using MODFLOW (Christenson and others, 2011; Blome and Smith, 2012).

Several U.S. Geological Survey (USGS) projects, supported by the National Cooperative Geologic Mapping Program (NCGMP), have used multi-disciplinary approaches over a 14-year period to reveal the surface and subsurface geologic frameworks of the Edwards and Trinity aquifers of central Texas and the Arbuckle-Simpson aquifer of south-central Oklahoma (fig. 1). Some of the project achievements include advancements in hydrostratigraphic mapping, 3D subsurface framework modeling, and airborne geophysical surveys as well as new methodologies that link geologic and groundwater flow models (Blome and others, 2007; Blome and Smith, 2012). One area where some of these milestones were achieved was in and around the U.S. Army Camp Stanley Storage Activity (CSSA), located in northwestern Bexar County, Texas, about 19 miles northwest of downtown San Antonio (fig. 1).

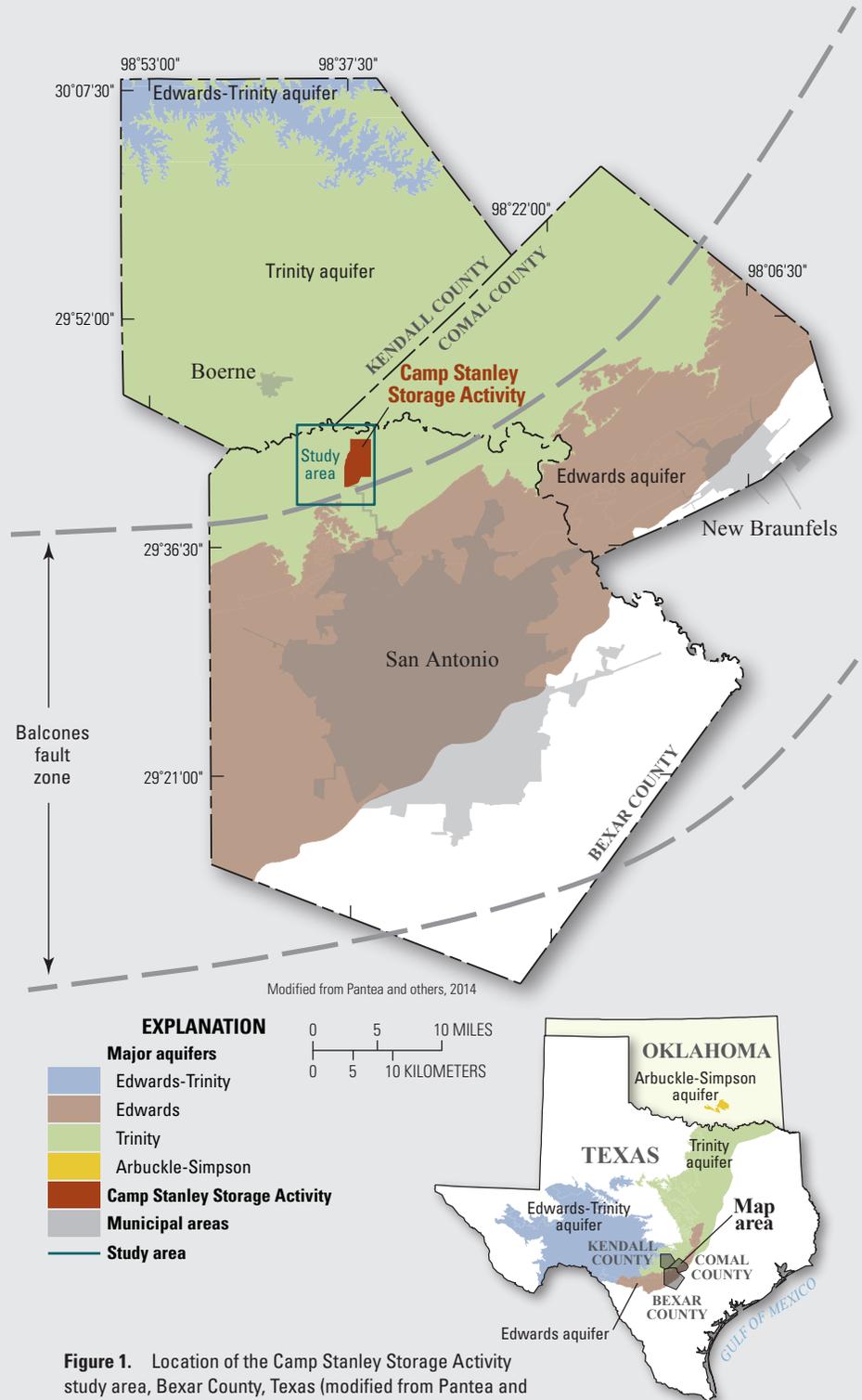
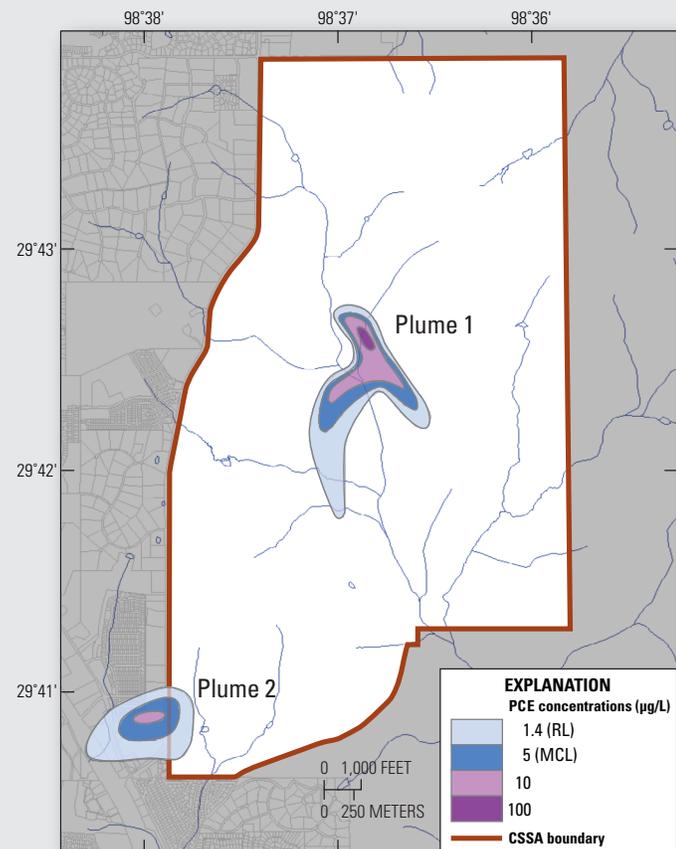


Figure 1. Location of the Camp Stanley Storage Activity study area, Bexar County, Texas (modified from Pantea and others, 2014).

Camp Stanley Storage Activity and Solvent Contamination

Camp Stanley encompasses approximately 4,000 acres and borders Camp Bullis, a much larger military base to the east and southeast. Between 1906 and 1907, six tracts of land were purchased by the U.S. Government and designated the Leon Springs Military Reservation. In October 1917, the installation was designated Camp Stanley. In 1933, Camp Stanley was selected as an ammunition depot, and its current mission remains the receipt, storage, issuance, and maintenance of ordnance, in addition to quality assurance testing and maintenance of military weapons and ammunition (Pearson and Murphy, 2004; U.S. Environmental Protection Agency [EPA], 2015).

Extended military operations at Camp Stanley since the early 1900s have contaminated both the soils and groundwater in and off the base. Environmental investigations began at the CSSA in 1991 after the Texas Department of Health discovered elevated levels of the dissolved cleaning solvents tetrachloroethane (PCE), trichloroethane (TCE), and *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) above the regulatory maximum contaminant levels. Other volatile organic compounds (VOCs) were discovered in a sample from a CSSA well located near the center of the CSSA. Follow-up studies confirmed that VOC contamination in nearby wells had even higher contaminant concentrations. One source of solvent contamination, known as Plume 1 (fig. 2), was identified as a former oxidation pond. Another area of solvent contamination, known as Plume 2 (fig. 2), is located in the southwestern corner of the base (U.S. Army, 2001; EPA, 2015). Starting in 1996, the first of 122 monitoring wells were installed (S.W. Pearson, Parsons, Austin, Texas, written commun., 2017). For more information, go to the CSSA website at <https://www.stanley.army.mil/>.



Parsons, 2017

Figure 2. Camp Stanley Storage Activity (CSSA) plume concentrations (used with permission by Parsons, Austin, Texas. PCE, tetrachloroethylene; µg/L, microgram per liter; RL, reporting limit; MCL, maximum contaminant level).

The release of these solvents resulted in the contamination of the Middle Trinity aquifer, which is the primary water source for the military base and surrounding areas. The lower member of the Glen Rose Limestone, and Bexar Shale and Cow Creek Limestone Members of the Pearsall Formation, form the Middle Trinity aquifer (fig. 3). The lower member of the Glen Rose Limestone was initially subdivided into six informal hydrostratigraphic units, known as units A–F (fig. 3) by Blome and Clark (2014). These informal units were later named and described by Clark and Morris (2015) as the Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust, and Honey Creek hydrostratigraphic units (fig. 3). Locally, the underlying Bexar Shale Member serves as the lower confining unit between the water-bearing Glen Rose Limestone and the Cow Creek Limestone Member of the Pearsall Formation (Pearson and Murphy, 2004).

Discussions with the CSSA Environmental Program Manager in 2009 led USGS personnel to coordinate several meetings with staff from the CSSA Environmental Office, the EPA, Parsons, and other CSSA cooperators. A number of topics were discussed at these meetings, and foremost among them was the need to better understand the local geology and the direction of contaminant flow both in the CSSA and residential areas south and west. Shortly thereafter, the USGS developed several Scope of Services Agreements (SOSAs) with the CSSA with the following objectives to be accomplished within a two-year period.

System	Group	Formation	Member	Thickness (meters)	Aquifer	Zone	Mapped hydrostratigraphic units, colors keyed to fig. 6	Model hydrostratigraphic units, colors keyed to figs. 4, 7, 8		
Lower Cretaceous	Edwards	Kaizer Fm.	Dolomitic	32–42	Edwards	Undefined	Kirschberg Evaporite (Kkke)	Edwards aquifer (Edwards in model)		
			Basal nodular	35			Dolomitic (Kkd)			
	Trinity	Glen Rose Limestone	Upper Glen Rose	35	Trinity	Upper	Cavernous (Kgrc)	Upper Trinity aquifer (Upper Glen Rose in model)		
				35–44			Camp Bullis (Kgrcb)			
				5–7.5			Upper evaporite (Kgrue)			
				70–85			Fossiliferous (Kgrf)			
				1.8–4.7			Lower evaporite (Kgrle)			
			Lower Glen Rose	11			Middle		Bulverde (Kgrb)	A
				11.8					Little Blanco (Kgrlb)	B
				20.1					Twin Sisters (Kgrts)	C
				13.3					Doeppenschmidt (Kgrd)	D
				21.6					Rust (Kgrrr)	E
	18.6	Not present	F							
	Pearsall Formation	Hammett/Cow Creek/Bexar Limestone/Shale	18.6	Lower	Confining unit	**		Bexar		
			21.9			**		Cow Creek		
Hosston Sligo	*	*	~35	Lower	Lower	**		**		
			~105			**		**		

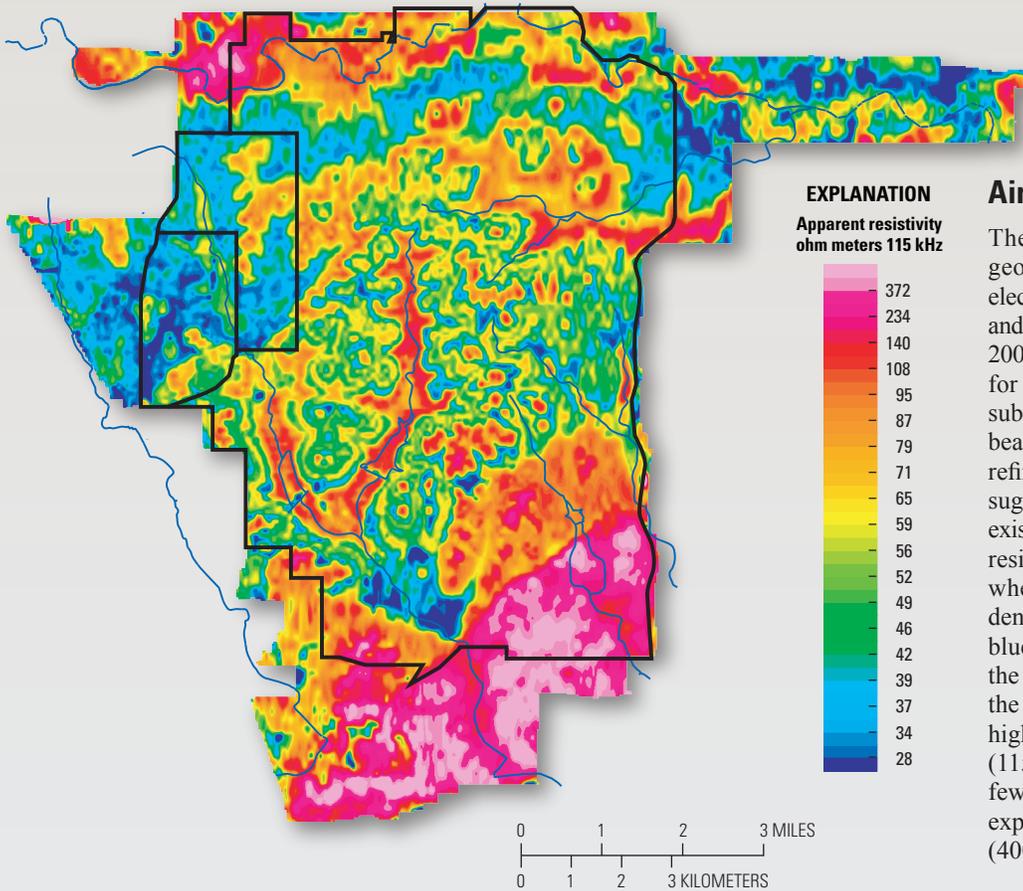
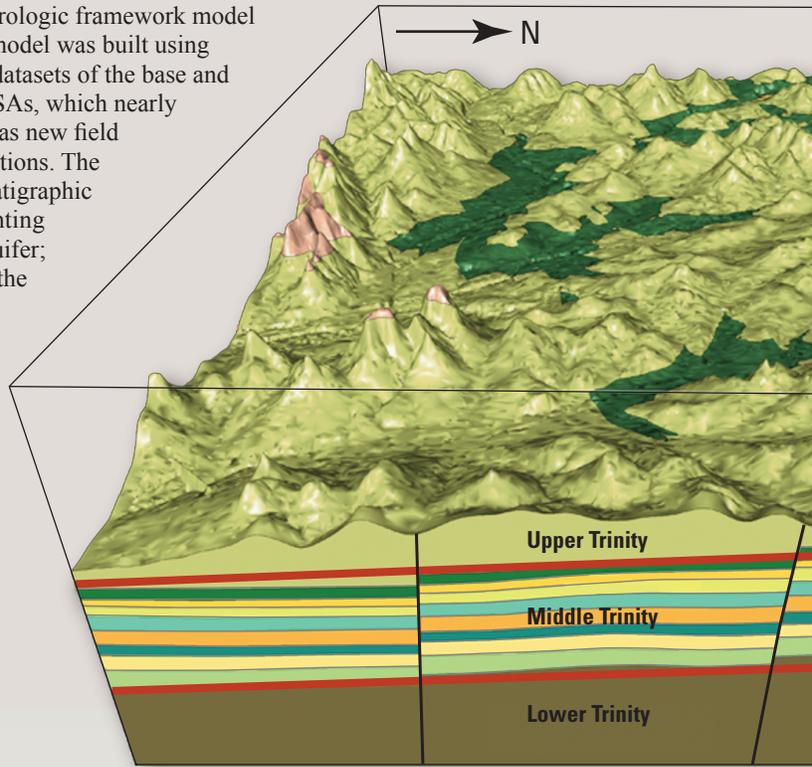
*Not subdivided into members.
**Not mapped or subdivided hydrostratigraphically.

Figure 3. Lithostratigraphic and hydrostratigraphic correlation of mapped and modeled units in the Camp Stanley Storage Activity area (modified from Pantea and others, 2014).

1 Objective 1. Construction of the 3-D EV Model of the CSSA and Areas South and West

The first objective identified was the construction of a 3D geohydrologic framework model using the 3D software called EarthVision™ (EV). The interactive 3D model was built using surface hydrostratigraphic maps and subsurface borehole geophysical datasets of the base and areas west and south. A number of modifications were made to the SOSAs, which nearly doubled the size of the 3D model area. Included in the modifications was new field mapping to accurately locate all modeled faults and verify all well locations. The 3D EV model (fig. 4) was completed in 2013 and contains 11 hydrostratigraphic units (fig. 3) in descending stratigraphic order: 1 model layer representing the Edwards aquifer; 2 model layers representing the Upper Trinity aquifer; and 9 model layers representing the Middle Trinity aquifer. The top of the Hammett Shale Member (fig. 3) is the lowermost model unit and was used to propagate and validate fault structures and drill-hole data.

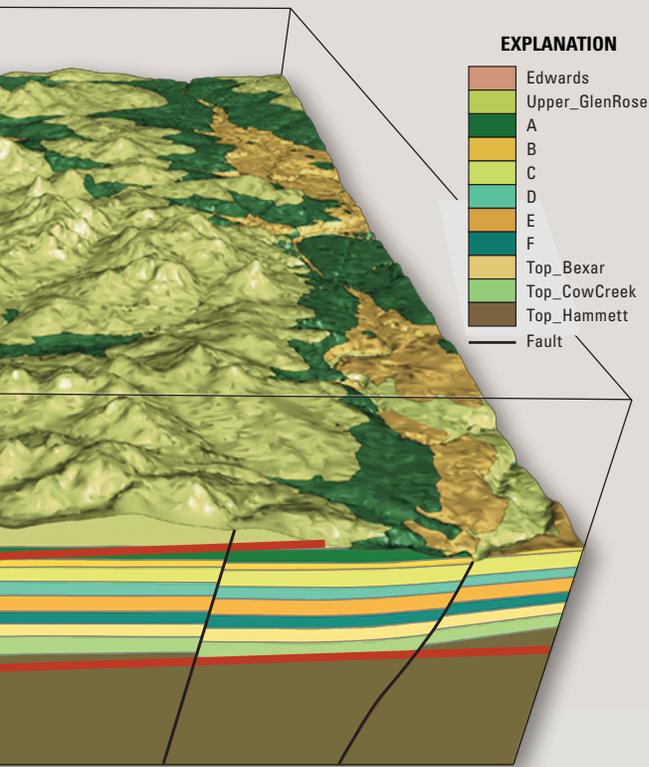
Figure 4. Camp Stanley Storage Activity three-dimensional EarthVision™ model showing model area, surface topology, subsurface model units, and fault structures (black near-vertical lines). Rocks of the Edwards aquifer (in pink) cap some of the hills in the southern part of the study area. View is from the east looking west (modified from Pantea and others, 2014).



Airborne Geophysics

The 3D EV model also incorporated geophysical data from the helicopter electromagnetic (HEM) survey of the CSSA and Camp Bullis (fig. 5) flown in December 2003 (Smith and others, 2005). The objective for flying the HEM survey was to study the subsurface electrical resistivity of aquifer-bearing geologic features. This survey also refined the location of mapped faults and suggested that many more unmapped faults exist. The higher order colors (reds) indicate resistive lithologies, such as limestone, whereas the lower order colors (blues) denote mudstone and shale. Heavy, wavy blue lines represent the major drainages of the study area, and the black lines denote the boundaries of the military bases. At the highest electromagnetic (EM) frequency (115 kHz), the exploration depth is only a few meters at most whereas the maximum exploration depth at the lowest frequency (400 Hz) is on the order of 100 meters.

Figure 5. Helicopter electromagnetic survey of the Camp Stanley Storage Activity and adjacent Camp Bullis, located just north of San Antonio, Texas. The highest electromagnetic frequency of 115 kilohertz (kHz) defines the geoelectric signatures of near surface strata (Smith and others, 2005).



Geologic Mapping

The Lower Cretaceous geology of the CSSA area is characterized by alternating and intermixed sequences of shale, sandstone, carbonate, and evaporitic rocks assigned to the Trinity Group (Clark and others, 2016). The overlying Edwards Group contains carbonate, chert, and evaporitic rocks. The Trinity Group rocks were formed on a large, shallow marine carbonate platform (Comanche shelf), whereas Edwards Group rocks were formed in open marine to supratidal flat depositional environments.

The geologic map of northern Bexar County, Texas (Clark and others, 2009), was used to construct and constrain the CSSA 3D EV model (fig. 4). This map was later updated by Clark and others (2016) and describes and illustrates both the lithostratigraphy and hydrostratigraphy of the lower part of the Edwards aquifer down to the uppermost middle Trinity aquifer (fig. 6). Within the 3D EV model area, the lower part of the Edwards aquifer is present and includes the Dolomitic and Basal nodular hydrostratigraphic units. Rock outcrops associated with the Edwards aquifer cap only the hilltops south of the CSSA (fig. 6) and do not represent aquifer recharge areas within the 3D model area.

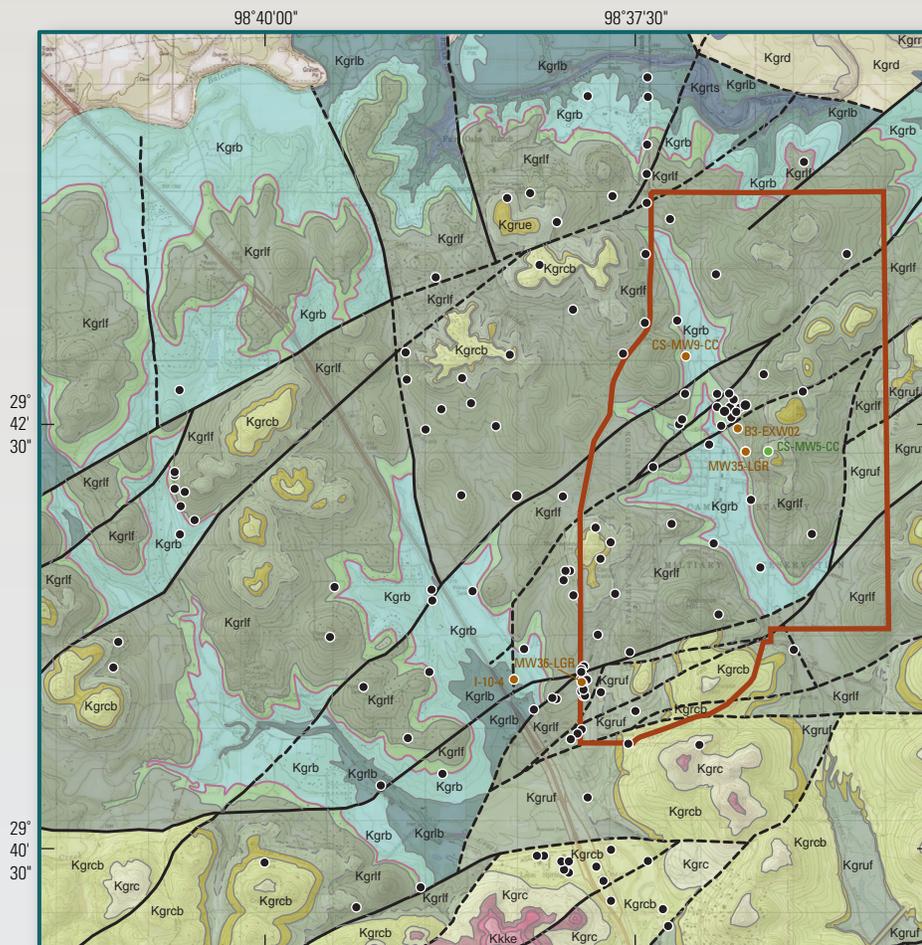
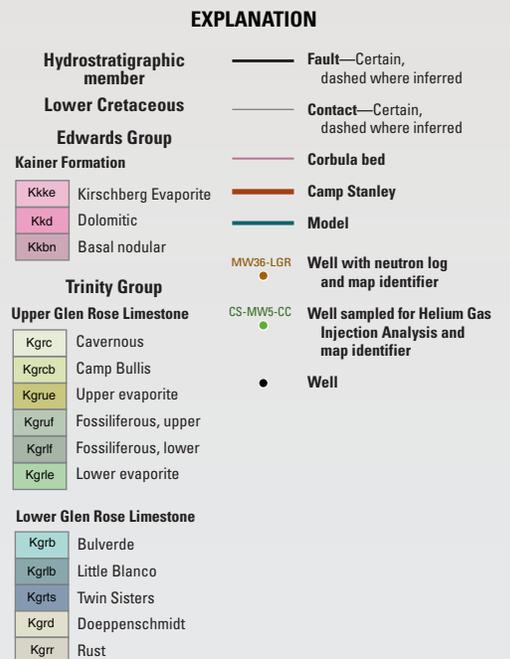


Figure 6. Geologic map of the Camp Stanley Storage Activity (CSSA) three-dimensional (3-D) model area (fig. 1) showing both lithostratigraphic and hydrostratigraphic units, mapped faults, and well locations (Clark and others, 2016). Red outline represents the CSSA boundary; blue-green outline represents the area encompassed by the CSSA 3-D EarthVision™ model of Pantea and others (2014).



Base modified from U.S. Geological Survey 1:24,000-scale digital data
 Universal Transverse Mercator projection, zone 14
 North American Datum of 1983



1 Objective 1. Construction of the 3-D EV Model of the CSSA and Areas North and West

Fault Structures

Faults in northern Bexar County are part of the Miocene-age Balcones fault system historically called the Balcones fault zone (fig. 1). The southwest- to northeast-trending Balcones fault zone is an extensional system of normal en echelon faults that are downthrown to the southeast, and locally, high-angle normal faults are common. The CSSA 3D EV model (Pantea and others, 2014) revealed previously undetected horst and graben structures in the northeastern and southern parts of the study area. One graben was identified in the northeastern part of the study area and trends northeast to southwest (fig. 7). This graben structure may control or alter local groundwater flow as well as flow direction.

In the CSSA model area, fault dips were interpreted to range from 52 to 75 degrees based on field mapping and drill-hole data (Clark, 2004). Although most fault displacements identified in the study area are 6 meters or less, a series of closely spaced faults near the southern boundary of the CSSA had greater displacements and one fault, located in the south-central part of the study area, exhibited up to 60 meters of displacement (fig. 8).

Figure 7. Horst and graben structures in the northeastern part of the Camp Stanley Storage Activity model area. View is from the northeast looking southwest (Pantea and others, 2014).

EXPLANATION	
	Edwards
	Upper_GlenRose
	A
	B
	C
	D
	E
	F
	Top_Bexar
	Top_CowCreek
	Top_Hammett
	Fault

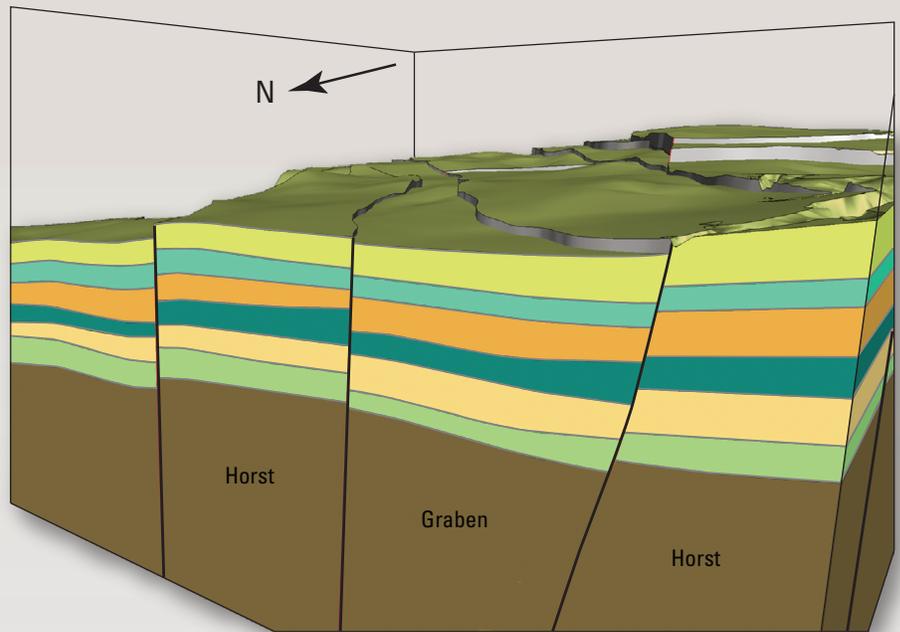
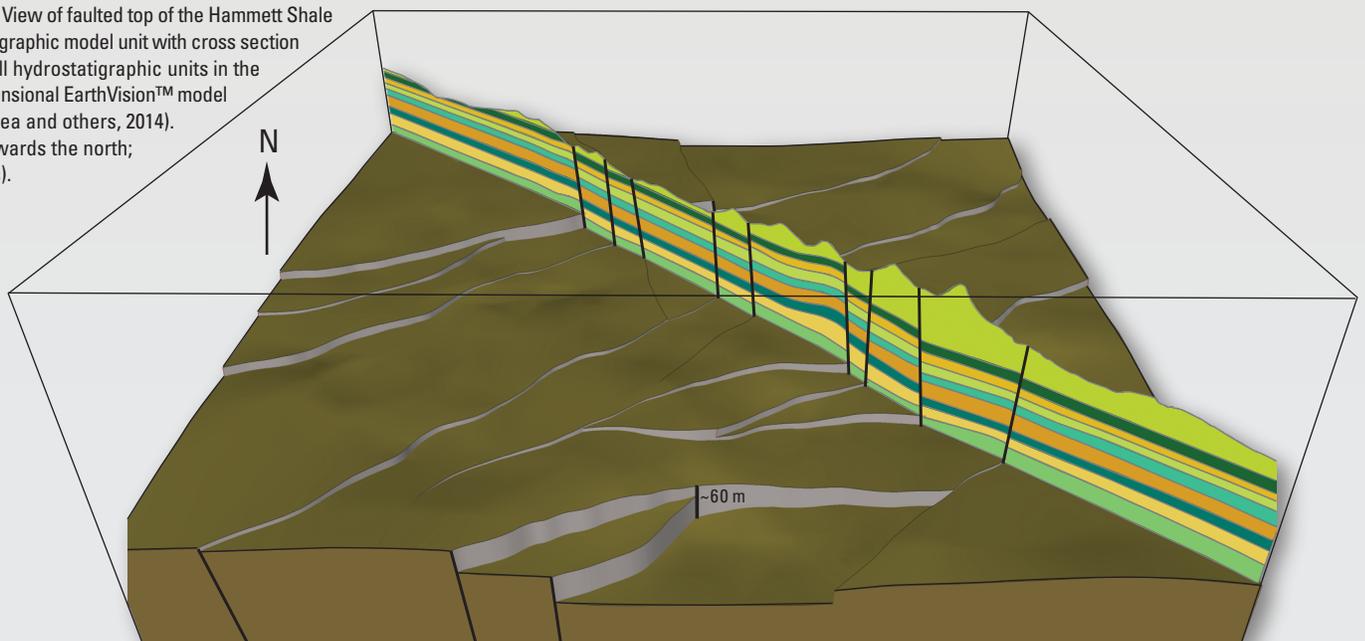


Figure 8. View of faulted top of the Hammett Shale hydrostratigraphic model unit with cross section showing all hydrostratigraphic units in the three-dimensional EarthVision™ model area (Pantea and others, 2014). View is towards the north; (m, meters).



2 Objective 2. Downhole Geophysical Logging

The USGS analyzed and interpreted borehole geophysical data from 12 wells logged by the USGS during 2012 to supplement existing borehole data under Objective 2. The geophysical data included nine wells located on the military facility and three off base. Of particular note was the logging of two wells, MW9-CC and MW5-LGR, by the USGS to depths of more than 470 and 450 feet, respectively. Refer to Blome and Clark (2014) for details on the

logging of these wells. Of the 12 wells, 4 were logged with a neutron geophysical tool to obtain effective porosity data. Neutron porosity measurements employ a neutron source to measure the hydrogen index in a reservoir, which is directly related to porosity in downhole formations. Borehole geophysical data collection included three mobilizations of logging equipment that were operated and maintained by the USGS (<https://tx.usgs.gov/>).

3 Objective 3. Porosity and Permeability Measurements

Two cores from wells MW9-CC and MW5-LGR were provided by the CSSA and shipped to the USGS Core Research Center (Denver, Colorado) for storage, slabbing, and preparation for petrophysical analysis. Lithologic character and type of observed porosity for all Glen Rose Limestone hydrostratigraphic units were described by Blome and Clark (2014) following the porosity classification of Choquette and Pray (1970) and the classification system of Dunham (1962).

Under Objective 3, 55 core plugs from well MW5-LGR, from intervals representing the lower member of the Glen Rose Limestone (fig. 3), were submitted to Weatherford Laboratories, Inc., (Golden, Colorado) for helium-gas-injection porosity and permeability analyses. Gas injection (also called gas expansion) is one of the accepted methods for measuring core or plug porosity and permeability and is preferred when analyzing poorly consolidated samples.

Porosity values (ambient, in porosity percent) for the lower member of the Glen Rose Limestone range from 6.0 percent to 30.2 percent, with a mean porosity value of 17.8 percent. Permeability values (to air, in millidarcys) were 0.0043 to 406 with a mean permeability of 14.7 (Blome and Clark, 2014). The helium injection porosity and permeability values and neutron geophysical log data will be used to construct future 3D property models for areas in and around the CSSA. Much of the funding for the CSSA 3D modeling and downhole geophysical and petrophysical data was through shared funding from the USGS National Cooperative Geologic Mapping Program and the CSSA Environmental Program.

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